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Seismic Study of Crustal Structure in Pennsylvania and New York

LAMONT GEOLOGICAL OBSERVATORY

(Columbia University)

Palisades, New York

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Technical Report No. 32

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Seismic Study of Crustal Structure in Pennsylvania and New York

by

Samuel Katz

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ABSTRACT

Blasts at two quarries in northern New York and central Pennsylvania have been recorded to a distance of 309 km. The data indicates an essentially homogeneous crust, with elastic wave velocities possibly increasing with depth. An average crustal thickness for the region is 34.4 km, with no indication of significant difference in thickness between the two areas. Observed compressional wave velocities for the crust are 6.3, and 6.31 km/sec for New York, and 6.04 km/sec for Pennsylvania. The corresponding shear wave velocities are 3.62 and 3.60 km/sec, and 3.61 km/sec. Average upper mantle velocities are 8.14 km/sec for P_n and 4.69 km/sec for S_n. The compressional wave velocity of anorthosite near Tahawus, N. Y. is 6.63 km/sec. No near-vertical reflections from the Mohorovicic discontinuity were observed.

I. INTRODUCTION

A number of large explosions set off in the course of the quarry operations of the Bethlehem Quarry Company at Milroy, Pennsylvania, and of the National Lead Company, Titanium Division, at Tahawus, N. Y., have been recorded during the past three years. Portable field recording equipment described briefly below was used at the quarries and at field sites at distances up to 309 km. The data for the Tahawus profiles were obtained during September 1950 and July and August 1951 by J. G. Heacock, Jr., D. J. Shriner, and Samuel Katz. The data for the Milroy profile was obtained on the various dates shown in Table I-C by the above, and by W. Beckmann, C. Bentley, J. Dorman, P. Du Bois, J. Oliver, F. Press, L. Shurbet, E. Smith, H. Smith, G. H. Sutton, and D. Warren.

Figure 1 shows the location of the quarries and the recording sites. The directions of the profiles were dictated largely by availability of roads, time, and personnel, although, when possible, stations were located to give maximum path through the oldest basement rocks. Two profiles were obtained from Tahawus in an effort to determine the azimuthal dependence of seismic velocities and the variation, if any, of depth to the Mohorovicic discontinuity. Tables I-A, I-B, and I-C list the recording sites, their location and elevation, and the topographic

sheet on which they may be found. Tables II-A, II-B, and II-C give the shot times, dates, and positions.

The Tahawus-west profile begins in the southwest corner of the Adirondack anorthosite body near the center of the Adirondack igneous complex.[1] Only the path to the first station, Santanoni (4.29 km), lies entirely within anorthosite. From Moose Pond (11.58 km) out to Antwerp (125.60 km) the rocks are pre-Cambrian granites. At Theresa (141.87 km) and Fisherman's Landing (159.63 km) the rocks are Potsdam sandstone of Cambrian age. At the farthest three stations, in Ontario, the rocks are pre-Cambrian and lower Cambrian in age.

On the Tahawus-south profile the anorthosite extends some 3 km south from the quarry. Beyond this from Tahawus Club (11.05 km) to Barkersville (106.49 km), the rocks are pre-Cambrian granites and grano-syenite intrusions. Beyond Galway (114.49 km), the stations were set on younger rocks, including Cambrian dolomite, Ordovician shale, and Devonian limestone.

On the Milroy profile the rocks have a much greater age range, from pre-Cambrian gneiss in central New Jersey, Cambrian limestones in central Pennsylvania to Triassic diabase at Palisades, N. Y. (309.09 km).

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1. A. F. Buddington, Adirondack Igneous Rocks and Their Metamorphism, G.S.A. Memoir #7, 1939; Geologic Map of New York, F. J. H. Merrill, New York State Museum, 1901.

II. EQUIPMENT

Each field station was equipped with one vertical and one horizontal seismometer, of the moving-coil type, with a free period of about 0.3 seconds. These instruments were designed to be used either as vertical or horizontal seismometers with slight modification. The seismometer signals were amplified and recorded on a Brush two-channel recorder. A chronometer, calibrated by WWV time signals, provided time marks on an auxiliary trace.

For the Milroy profile, usable records were obtained from short-period Benioff seismograms, as well as from a short-period Columbia vertical seismometer, at Lamont Geological Observatory, Palisades, N. Y. (309.09 km).

At the quarries, vertical geophones served as detectors, and various recording methods were used, depending upon the availability of personnel. During September 1950 at Tahawus, N. Y., a completely automatic installation turned on all recording gear during the blast period from 4:30 to 5:30 P. M. Chronometer calibrations had to be made following the blast.

At the other blasts one or two channel Brush recorders were used to record the ground motion near the shot. A chronometer, calibrated by WWV time signals, provided the time scale.

III. DISTANCE DETERMINATION

The positions of all recording sites were determined from the most recent topographic sheets of the U.S. Geological Survey or the Army Map Service. The Thurman station was located on the North Creek sheet for which no recent editions are available, and which was surveyed by reconnaissance methods.

The position of shots on the Milroy profile was determined from the U.S. G.S. Lewistown, Pa. sheet. The topographic sheet for the Tahawus area could not be used for this purpose, since it was surveyed by reconnaissance methods. However, the detailed map of the mining area, made available to us by the National Lead Company, included a U.S.G.S. Bench Mark, whose latitude and longitude were accurately known. This made it possible to determine the location of all shots.

Rather than convert all latitudes to their geocentric value and find the value of the shot distance from the exact formula, we used the simple and convenient tables and method described by C. F. Richter.[1] The error in distance determination resulting from this method is less than one part in 5000 out to distances of 500 km. The difference between the chord and arc distance is negligible.

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1. C. F. Richter, Calculation of Small Distances, Bull. S.S.A., 33, 4, pp. 243-250, Oct. 1943.

IV. TIME DETERMINATION

The seismograms on the Milroy profile and on the Tahawus-west profile were timed by Negus, and Ulysse Nardin one-second, break-circuit chronometers, and by Chelsea one-second break-circuit clocks. These were calibrated by the radio time signal of WWV, National Bureau of Standards before and after the shot. On the Tahawus-south profile, the WWV time signals were recorded directly on the seismogram along with the shot.

At both quarries the shots were timed by a Ulysse Nardin one-second, break-circuit chronometer which was checked against WWV time signals, usually before and after the blast, when possible. On the Tahawus-west profile, 1950, an automatic recording system requiring manual time checks was used. These had to be made as much as eight hours before and after the blast. However the chronometer had a fairly constant rate, and its calibration was reliable.

The paper speed for shots recorded from Tahawus was 5 mm per second, because the uncertainty of the shot time made it necessary to record for at least one hour. On the Milroy profile, charges were detonated on a pre-set schedule, and all records were obtained at a paper speed of 25 mm per second.

V. CORRECTIONS

On the Milroy profile, the geophone and recording equipment were set up as close to the blast as safety permitted. The distance from the geophone to the center of the array of shot holes was measured. Assuming a compressional wave velocity of 6.0 km/sec for the quarry limestone, the correction for the travel time to the geophone was applied to all shot instant times. This correction was always less than .06 seconds.

On the Tahawus profiles, the shot instant correction was considerably more difficult to obtain for several reasons. Neither the compressional wave velocity in anorthosite nor the delay in the shot recording equipment were known. Furthermore, the distance between the shot geophone and the center of the array of shot holes was quite variable, ranging from 350 to 1171 feet.

To overcome these difficulties three blasts were accurately timed by three sets of recording gear set up on anorthosite rock at various distances and azimuths in the vicinity of the quarry. The results of this measurement described in Section IX, yielded both the compressional wave velocity in anorthosite and the delay in the shot recording equipment.

The shot-geophone distances were obtained from the detailed mine maps kindly made available by the National Lead Company. These distances and the velocity in anorthosite determined above gave the shot

instant correction for each of the recorded blasts.

For seismograms on which P_n and S_n were recorded, a correction reducing the shot and listening stations to sea level was applied. If h_s and h_l are the elevations in feet above sea level of the shot and listening stations respectively, V_1 the average crustal velocity, and V_n the velocity beneath the Mohorovicic discontinuity, this correction is given by

$$\frac{2(h_s + h_l)}{V_1} \sqrt{1 - \left(\frac{V_1}{V_n}\right)^2}$$

The corrections in seconds were $0.69 \times (h_s + h_l) \times 10^{-4}$ for the Milroy profile, and $0.61 \times (h_s + h_l) \times 10^{-4}$ for the two Tahawus profiles.

The analagous corrections for the shear waves were $1.1 \times (h_s + h_l) \times 10^{-4}$.

VI. DATA AND DESCRIPTION OF PHASES

The travel time-distance data obtained on three profiles are listed in Tables III-A, III-B, and III-C and shown in Figures 2, 3, and 4.

On all three profiles, the first arrivals out to a distance of 190 km have been identified as P_1. At stations within approximately 70 kilometers of the shot, the first arrivals are strong and unambiguous. For distances of 70 to 95 km the onset of the signal is complicated. For example, at Bear Gap, Pa. (93.99 km), at Star Lake, N. Y.

(81.67 km), and at Hadley Hill (78.88 km), the seismograms began with small amplitude lasting approximately one second, followed by a signal some four times larger than the onset. This signal appears on the seismogram obtained at Bear Gap, Figure 5-A. Beyond 95 km, on the Tahawus-west profile, all beginnings for P_1 are clear except Pitcairn (95.70 km). On the Tahawus-south profile, all stations out to Galway (114.49 km) show strong beginnings. Rynex Corners (134.99 km) and Diamond Rock (145.23 km) have weak beginnings, but P_1 is well recorded at Malden Bridge (181.39 km) from a charge twice as large. On the Milroy profile, there are strong onsets for P_1 at all distances except Bear Gap (93.99 km) and Oneida (122.20 km).

A cursory examination of the travel-time curves, Figures 2-4, reveals that there are no sharp breaks for distances less then 180 km. Accordingly only two crustal models were used in an attempt to fit the observed data. The first consisted of a crust with constant velocity down to the Mohorovicic discontinuity. The travel time equations for this model are

$$(1)\quad T_1 = \frac{\Delta}{V_1} \qquad \text{and} \qquad T_n = I + \frac{\Delta}{V_n}$$

where Δ is the range, V_1 and V_n the elastic wave velocities of the crust and upper mantle, respectively, T the travel time, and I the intercept of the travel time curve, related to the thickness of the crust H by

$$H = \frac{I}{2\sqrt{\left(\frac{1}{V_1}\right)^2 - \left(\frac{1}{V_n}\right)^2}} \tag{2}$$

The second model consisted of a crust in which the elastic wave velocities increased linearly with depth down to the Mohorovicic discontinuity. There is little to be gained from using more complicated velocity-depth relations at this time.

The travel time equation [1] is

$$T = \frac{2}{g} \sinh^{-1} \frac{g\Delta}{2V_0} \tag{3}$$

where g is the elastic wave velocity gradient with depth in km/sec/km, and V_o is the surface velocity. Following Willmore, Hales, and Gane,[2] (3) may be expanded into

$$T = \frac{\Delta}{V_0}\left[1 - \frac{1}{24}\left(\frac{g\Delta}{V_0}\right)^2 + \frac{3}{640}\left(\frac{g\Delta}{V_0}\right)^4 + \cdots\right] \tag{4}$$

For the distances of these observations, only the first two terms are needed, giving

$$T = a\Delta + b\Delta^3, \text{ where}$$
$$a = \frac{1}{V_0} \text{ and } b = -\frac{g^2}{24V_0^3} \tag{5}$$

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1. Maurice Ewing and L. Don Leet, Seismic Propagation Paths, Technical Publication No. 267, The American Institute of Mining and Metallurgical Engineers.

2. P. L. Willmore, A. L. Hales, and P. G. Gane, A Seismic Investigation of Crustal Structure in the Western Transvaal, Bull. S. S. A., 42, 1, pp. 53-80, Jan. 1952.

In Table IV, the travel time equations for the data of the three profiles have been obtained by means of the least squares method. The uncertainties listed in Table IV are probable errors.[1]

On all three profiles the travel time curve of first arrivals shows a break at a distance of some 190 km. The arrivals beyond this break are designated P_n and, on the basis of the velocity and intercept of their travel time curves, as well as the distance where they first appear, are identified as refractions from beneath the Mohorovicic discontinuity.

On the Tahawus-west profile only one P_n arrival at Odessa, Ontario (220.47 km) is clear and sharp. At Roslin, Ontario (265.26 km), the onset is weak and uncertain within about one second. The closer records do not show P_n as second arrivals, as do the records at comparable distances on the other two profiles. If we assume a velocity for P_n of 8.2 km/sec, and force the line through this point, we find an intercept of 6.8 sec.

On the Tahawus-south profile, P_n was observed both as second and first arrival. Only three arrivals were identified as S_n. Assuming a velocity of 4.7 km/sec for S_n, we find the intercept graphically as 13.3 seconds.

On the Milroy profile, strong P_n and S_n arrivals were observed out to a distance of 309 km.

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1. For a clear and useful discussion, see R. T. Birge, The Calculation of Errors by the Method of Least Squares, Phys. Rev. Vol. 40, pp. 207-227, 1932.

VII. INTERPRETATION

If one assumes that the crust is a uniform plate with seismic properties described by the travel time equations of Table IV, one is led to an unambiguous determination of the thickness of this plate. Using (1) and (2), the results are (thickness obtained on the basis of assumed velocity for P_n or S_n is in brackets):

Tahawus west:

Compressional waves:	[34. 8 km]
Distortional waves:	38. 1±3. 6 km

Tahawus south:

Compressional waves:	36. 0±2. 0 km
Distortional waves:	[37. 2 km]

Milroy:

Compressional waves:	32. 7±3. 3 km
Distortional waves:	36. 3±4. 3 km

An alternative interpretation to which the data can be fitted is a gradual increase of seismic velocities with depth. The range of velocity gradients for the distortional waves given in the previous section is from . 0066 to 0. 011 km/sec/km. It was possible to fit the linear increase hypothesis for the compressional waves only to one profile, giving a gradient of . 025 km/sec/km. This circumstance results from the fact that on the Tahawus-south and Milroy profiles there are observations of P_1 at ranges beyond 250 km at practically the same velocity as the close-in observations of P_1.

To show that the values of velocity gradient we have obtained are compatible with the values of crustal thickness obtained on the previous assumption, we use the result that the maximum depth of penetration is approximately

$$Z = \frac{g\Delta^2}{8V_0}$$

For $g=248 \times 10^{-4}$ km/sec/km, and Z=40 km, we find Δ =285 km; so that P_1 could be observed out to this distance, without being cut off at the lower boundary of the crust. Smaller values of g make it possible to observe P_1 to further distances.

It is interesting to observe that on two of the three profiles the travel time equation for S_1 has an appreciable intercept larger than its probable error, while that for P_1 does not. Such an effect would occur if Poisson's ratio diminished with depth near the surface.

In Section VI we have described three seismograms, obtained at distances of 78.88 km, 81.67 km, and 93.99 km and showing a small beginning followed within one second by a much larger arrival that could not be correlated with any arrivals on other seismograms. This prominent signal could not be a reflection from the Mohorovicic discontinuity, since at these distances it would appear 4 seconds after P_1. A reflector at a depth of 16 km would give a signal at the observed distance and travel time. If critical reflection is assumed, the velocity of this

reflector is 6.7 km/sec. However, the absence of refraction arrivals corresponding to the above at longer distances makes it difficult to interpret this prominent signal as a reflection from any discontinuity. A possible velocity-depth relationship which would explain the observed arrivals is a velocity minimum, such as is observed in the deep ocean (SOFAR channel). Such a velocity distribution would focus energy only at certain distances.

Willmore et al. report a series of arrivals at a distance of 90-120 km following P_1 by approximately 1 - 1.5 seconds, which may well be the same as those described above. Willmore gives two tentative explanations. One assumes a crust with velocity increasing with depth. These signals might then arise from energy which leaves the subsurface rockburst in an upward direction, is reflected at the surface, only to be focused back to the surface. The other assumes a two-layer crust. This signal would then be a critical reflection from a layer with a velocity of 6.83 km/sec at a depth of 15.5 km. Hodgson reports similar arrivals at two stations at distances of 66 km and 120 km.[1]

With less amplification, the small beginnings on the three seismograms (see Figure 5-A) described above might well be missed, and the first arrivals read late by over one second. A velocity com-

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1. A Seismic Survey in the Canadian Shield, I. Refraction Studies Based on Rockbursts at Kirkland Lake, Ontario; Publications of the Dominion Observatory, Ottawa, Vol. XVI, No. 5. Manuscript kindly made available by Dr. Hodgson.

puted using the large amplitude, second arrival would be considerably lower than the correct value. This might provide an explanation for the relatively low velocities (less than 6.0 km/sec) found for the upper part of the crust in many of the crustal studies prior to 1948.

In an effort to bring the interpretation of the seismic data from shallow-focus earthquakes and large surface explosions into agreement, Gutenberg postulated the existence of a layer of low velocity, with a minimum near 5.5 km/sec extending from a depth of approximately 15 km to a depth of 20 or 25 km, where it again increases to the base of the crust.[1]

Press and Ewing have described the efficient propagation of seismic shear waves of periods from 2 to 12 seconds over exclusively continental paths, and have named these waves Lg.[2] Although aware of the weight of considerable geophysical evidence against the presence of a layer of low shear strength so near the surface, they tentatively suggest, for lack of a more probable explanation, that a layer of low shear velocity near the base of the crust could provide the necessary wave guide for the observed, efficient propagation of Lg.

On a seismic refraction survey one would expect to observe a low velocity layer by anomalous amplitude variation with distance,

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1. B. Gutenberg, Structure of the Earth's Crust in the Continents, Science, 111, pp. 29-30, Jan. 1950.

2. Frank Press and Maurice Ewing, Two Slow Surface Waves Across North America, Bull. S.S.A., 43, pp. 219-228, July 1952.

and by strong vertical or near-vertical reflections. On the three profiles of this study, the initial amplitude appears small over a limited range; on the Tahawus-west profile, Star Lake (81.67 km) and Pitcairn (95.70 km); on the Tahawus-south profile, Rynex Corners (134.99 km) and Diamond Rock (145.2 km); and on the Milroy profile, Bear Gap (93.99 km) and Oneida (122.20 km). Unfortunately, because of high wind noise background at Diamond Rock, and instrumental difficulties at Oneida, the records were not clear, and more work is required to verify this point. An unsuccessful search was made in the records obtained near Tahawus for near-vertical reflections from deep discontinuities. Shot records at quarries are useless for this purpose because of the high level of reverberation lasting many seconds after the blast.

It is interesting to note that the determinations of crustal thickness, using shear waves, is 5-20 percent higher than the value obtained using compressional waves in the investigations of Willmore, and Hodgson, cited above, as well as the present.

If there should exist a low velocity layer some 10 km thick with a velocity near 5.6 km/sec near the base of the crust, all the values of crustal thickness which have been computed to date, including the values obtained in this investigation, would be approximately 10 percent too high. Furthermore, if the 10 km of low-velocity material should be particularly incompetent, it would have a high Poisson's

ratio, and a disproportionately low shear wave velocity, and would account qualitatively for the high value of crustal thickness obtained using shear waves.

Large amplitude arrivals appear on the Palisades seismograms (309.09 km) at 84.0 - 85.5 seconds, preceding S_1 by about 2.1 seconds. The arrival has a velocity of 3.64 - 3.68 km/sec. This velocity is slightly less than 3.71 km/sec which Hodgson found for large amplitude shear waves, and which he suggested may be an Lg phase.[1] There is insufficient evidence here to warrant adding tc Hodgson's thorough discussion.

On every seismogram of this study, the amplitude of the shear waves was greater than that of the compressional waves. Using explosions no larger than those of this study, it would be quite feasible to investigate the propagation of shear waves to greater distances, and possibly to study the transition between the shear waves of the upper crust, S_1, and the long period Lg phase.

It is interesting to observe that usable seismograms were obtained from Tahawus blasts which did not exceed 4.4 tons, while seismograms at comparable distances from the Milroy blasts were obtained from charges which ranged from 22.0 to 46.1 tons. The explosive used in the Tahawus operation consisted for the most part of 90 percent

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1. J. H. Hodgson, loc. cit.

gelatin, instantaneously detonated with Primacord connections between holes. On the other hand, the explosive used at Milroy has consisted largely of 60 percent gelatin and 40 percent ammoniate, detonated usually in five or more sections, the time interval between sections being of the order of 0.025 seconds. To what extent the type of rock (anorthosite at Tahawus, limestone at Milroy) and the method of firing offsets the large difference in charge size is not clear. But it is certain that for comparable distances clear records can be obtained from Tahawus with charges roughly one-fifth of those required from Milroy.

VIII. COMPARISON WITH RECENT INVESTIGATIONS

The regions investigated in this report are similar geologically to areas which have been studied and reported on previously.

The Tahawus-west and Tahawus-south profiles are comparable to the profile reported on by Hodgson in the Kirkland Lake area of Ontario.[1] He finds, on the assumption of a single uniform crustal layer with a compressional wave velocity of 6.246±0.015 km/sec, underlain by the mantle with velocity 8.176±0.013 km/sec, a thickness of 36.4±1.5 km. The corresponding values for the distortional waves are 3.544±0.023 km/sec, 4.85±0.10 km/sec, and 44.1±14.7 km.

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1. J. H. Hodgson, loc. cit.

Willmore et al.[1] report two alternative interpretations of their rockburst data in the western Transvaal. Assuming a single uniform layer, they find 6.09±.02 km/sec, underlain by 8.27±0.04 km/sec material, leading to a crustal thickness of 34.2±0.8 km. The corresponding distortional wave values are 3.68±.02 km/sec, 4.83±0.02 km/sec, 38.2±1.0 km.

Slichter[2] finds in Wisconsin a fairly homogeneous layer some 40-44 km thick, with a velocity increasing from 6.0 km/sec near the surface to 7.0 km/sec at the bottom, and underlain by 8.17 km/sec. An alternative interpretation is a layer with a constant velocity of 6.16-6.26 km/sec.

References to older investigations are available in papers by Hodgson, cited above, and Gutenberg.[3]

IX. COMPRESSIONAL WAVES IN ANORTHOSITE

To obtain the shot instant corrections at Tahawus, the compressional wave velocity in anorthosite had to be measured. Although an adequate correction could be obtained by using the average, near-surface velocity, obtained from the travel time curve, it was felt that the small expenditure of time required to measure this number was

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1. Willmore, Hales, and Gane, loc. cit.

2. L. B. Slichter, Crustal Structure in the Wisconsin Area, Report N9 onr-86200, Oct. 31, 1951.

3. Beno Gutenberg, Crustal Layers of the Continents and Oceans, Bull. G.S.A., 62, pp. 427-440, May 1951.

worth while, especially since the velocity for anorthosite is not given in the literature.

Accordingly, three recording stations set up on anorthosite near the mine recorded three small blasts. The data is summarized in Table V. The travel time equation is

$$T_i = \frac{X_i}{V_a} + T_o$$

where T_i is the arrival time at the ith station and T_o the origin time of a given blast. X_i is the distance to the ith station, and V_a the compressional wave velocity in anorthosite. For each blast a least squares solution of this equation for V_a and T_o has been carried out. The results are shown in Table V.

If we regard these velocities as measurements of a random sample of the anorthosite, we can compute the probable error for these velocity determinations. The velocity of compressional waves in the anorthosite in the vicinity of Tahawus, N. Y. is 6.63±0.09 km/sec. Knowing this velocity, the origin time, and the shot-to-geophone distance, we can compute the delay due to the shot amplifier and 1600 feet of signal wire connecting geophone and recorder. This is .05 seconds.

CONCLUSIONS

The velocities and crustal thicknesses are summarized in Table IV. The hypothesis of an essentially homogeneous crust with a

possible small velocity gradient explains the data adequately. Within the errors of the experiment, no appreciable difference was found in crustal thickness in western and southeastern New York and northeastern Pennsylvania. An average crustal thickness for this region is 34. km. No important difference was found in the crustal velocities on profiles from Tahawus in a westerly and southerly direction. The velocities for the two directions are:

West	P_1	6.43±.01 km/sec
	S_1	3.62±.03 km/sec
	σ	0.266±0.005
South	P_1	6.28±.02 km/sec
	S_1	3.60±.01 km/sec
	σ	0.255±0.004

The profile across northeastern Pennsylvania had significantly lower compressional wave velocities and lower Poisson's ratio (σ).

P_1	6.01±.03 km/sec
S_1	3.61±.01 km/sec
σ	0.218±0.007

Values for velocities of the upper mantle are

P_n	8.07±0.10 and 8.21±0.02 km/sec
S_n	4.68±0.02 and 4.69±0.03 km/sec
σ (Milroy)	0.258±0.006

The compressional wave velocity of anorthosite in the vicinity of Tahawus, N. Y. is 6.63±0.09 km/sec.

No near-vertical reflections from the Mohorovicic discontinuity were found.

A large arrival following one second after P_1 was observed on all three profiles at ranges of approximately 90 km, but could not be followed out to greater ranges.

There is an indication that at a range of 80 to 140 km, the amplitude of the first arrival is abnormally small. Further work is required to confirm this point, since its bearing on the possible existence of a low-velocity layer is very important.

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TABLE I-A

Recording Sites

Tahawus-west Profile

Station Name	Latitude N	Longitude W	Elevation Feet	Topo. Corr. Pn	Topo. Corr. Sn	USGS Sheet N. Y.	Dates Occupied
1. Santanoni						Santanoni	8-31-50
2. Moose Pond	44°02'.46	74°11'.44	1840			Santanoni	9-7-50
3. Duck Lake	44°06'.98	74°27'.02	1790			Long Lake	9-14-50
4. Legion Camp	44°08'.47	74°32'.91	1550			Tupper Lake	9-5-50
5. Lake Marion	44°07'.81	74°43'.10	2070			Tupper Lake	9-18-50 9-16-50
6. Star Lake	44°10'.10	75°03'.36	1450			Oswegatchie	9-6-50
7. Pitcairn	44°12'.70	75°13'.44	810			Oswegatchie	9-6-50
8. Antwerp	44°14'.99	75°35'.79	560			Antwerp	9-20-50
9. Theresa	44°14'.60	75°48'.04	420			Theresa	9-20-50
10. Fisherman's Landing	44°15'.65	76°01'.31	240			Grindstone	9-20-50
						ONTARIO	
11. Gananoque	44°21'.84	76°09'.30	325	0.04	.07	Gananoque	9-21-50
12. Odessa	44°16'.59	76°47'.10	400	0.04	.07	Sydenham	9-25-50
13. Roslin	44°20'.99	77°20'.33	510	0.05	.08	Tweed	9-25-50

TABLE I-B

Recording Sites

Tahawus-south Profile

Station Name	Latitude N	Longitude W	Elevation Feet	Topo. Corr. Pn Sec.	Topo. Corr. Sn Sec.	USGS Sheet N. Y.	Dates Occupied
1. Tahawus Club	43°57'.38	74°02'.39	1790			Newcomb	8-2-51
2. Aiden Lair	43°53'.69	74°01'.01	1600			Newcomb	7-13-51
3. Minerva	43°48'.56	74°00'.48	1720			Newcomb	7-12-51
4. Sodom	43°38'.92	73°59'.43	1300			North Creek	7-12-51
5. Thurman	43°30'.29	73°53'.74	1560	0.10	.16	North Creek	7-9-51
6. Roaring Branch	43°25.36	73°56.63	1000	0.06	0.10	Luzerne	8-1-51
7. Roundtop	43°24'.90	73°56'.11	960	0.06	0.10	Luzerne	8-23-51
8. Stony Creek	43°22'.33	73°52'.45	640	0.04	0.06	Luzerne	7-9-51
9. Hadley Hill	43°20'.94	73°57.60	1340	0.08	0.13	Luzerne	8-23-51
10. Deming Hill	43°17'.36	74°00'.56	900	0.05	0.08	Stony Creek	8-1-51
11. Fox Hill	43°11'.56	74°02'.46	1580	0.10	0.16	Broadalbin	7-11-51
12. Barkersville	43°05'.81	74°03'.15	1220	.07	.11	Broadalbin	7-31-51
13. Galway	43°01'.55	74°00'.58	780	.05	.08	Broadalbin	7-11-51
14. Rynex Corners	42°50'.44	74°03'.79	1240	.08	.13	Amsterdam	7-18-51
15. Diamond Rock	42°46'.76	73°39'.74	300	.02	.03	Cohoes	7-20-51 7-18-51

TABLE I-B (Cont.)

Station Name	Latitude N	Longitude W	Elevation Feet	Topo. Corr. Pn Sec.	Sn	USGS Sheet N. Y.	Dates Occupied
16. Altamont	42°40'.57	74°03.20	1420	.09	.14	Berne	7-18-51 7-23-51
17. Averill Park	42°37'.70	73°34'.50	620	.04	.06	Troy	7-20-51
18. Westerlo	42°31'.72	74°01'.07	1400	.09	.14	Berne	7-18-51
19. Malden Bridge	42°27'.68	73°34'.03	660	.04	.06	Kinderhook	8-14-51
20. West Copake	42°06'.88	73°38'.02	680	.04	.06	Copake	8-14-51
21. Fishkill	41°31.55	73°52'.14	460	.03	.05	Poughkeepsie	8-14-51

TABLE I-C

Recording Sites

Milroy Profile

Station Name	Latitude N	Longitude W	Elevation Feet	Topo. Corr. Pn Sec.	Topo. Corr. Sn Sec.	USGS or AMS Sheet	Dates Occupied
1. Middle Creek, Pa.	40°46'.57	77°16'.02	710			Millheim, Pa.	11-19-51
2. Freeburg, Pa.	40°45'.66	76°56'.16	600			Sunbury, Pa.	11-19-51
3. Bear Gap, Pa.	40°52'.07	76°28!.28	725	-.02	-.03	Mt. Carmel, Pa.	4-20-53
4. Oneida, Pa.	40°54'.51	76°07'.73	1700	-.06	-.10	Nuremberg, Pa.	10-3-51
5. Hudson-dale, Pa.	40°54'.19	75°49'.14	1700	-.06	-.10	Weatherly, Pa.	10-3-51
6. Aquashi-cola, Pa.	40°51'.92	75°35'.62	880	-.03	-.05	Mauch Chunk, Pa.	10-3-51
7. Kellers-ville, Pa.	40°56'.25	75°17'.65	680	-.02	-.03	Wind Gap, Pa.	10-3-51
8. Strouds-burg, Pa.	40°56'.98	75°09'.02	1360	-.05	-.08	Strouds-burg, Pa. -N. J.	8-16-51
9. Millbrook, Pa.	41°00'.47	75°05'.10	730	-.02	-.03	Bushkill, Pa.	8-21-52
10. Long Valley, N. J.	40°47'.60	74°46'.77	640	-.02	-.03	Hacketts-town, N. J.	8-16-51
11. Tranquil-lity, N. J.	40°55'.28	74°46'.54	840	-.03	-.05	Tranquil-lity, N. J.	4-20-53 4-21-52
12. Boonton, N. J.	40°57'.06	74°25'.41	700	-.02	-.03	Boonton, N. J.	4-20-53
13. Palisades, N. Y.	41°00'.42	73°54.52	230	-.01	-.02	Nyack, N. Y.	8-16-51 10-3-51 11-19-51 8-21-52 8-21-52 4-20-53 5-8-53 5-8-53

TABLE II-A

List of Shots

National Lead Company
Tahawus, N. Y.

Date 1950	Time EST	Shot Position Latitude N	Longitude W	Elevation Feet	Charge Size Tons
8-31	14:46:21.60	44°03'.34	74°02'.93	1753	0.5
9-7	14:46:38.60	44°03'.29	74°02'.85	1896	0.9
	15:00:18.09	44°03'.28	74°02'.92	1823	0.75
	15:29:00.45	44°03'.33	74°02'.75	1948	4.4
9-14	15:17:15.08	44°03'.28	74°02'.87	1893	0.75
9-5	14:39:53.18	44°03'.38	74°02'.92	1753	0.75
	15:08:00.11	44°03'.37	74°02'.77	1858	1.25
9-18	15:00:11.56	44°03'.31	74°02'.85	1858	1.5
9-6	14:49:09.49	44°03'.38	74°02'.87	1788	3.2
9-20	15:15:38.52	44°03'.31	74°02'.81	1893	1.9
9-21	14:56:50.76	44°03'.35	74°02'.89	1788	1.5
9-25	16:56:41.97	44°03'.33	74°02'.74	1948	3.95

Topographic correction for Sn: -0.2 sec.

Jones & Laughlin Ore Company
Star Lake, N. Y.

9-16	11:08:18.21	44°11'.67	74°59'.88	1450	7

TABLE II-B

List of Shots

National Lead Company
Tahawus, N. Y.

Date 1951	Time EST	Shot Position Latitude N	Shot Position Longitude W	Elevation Feet	Charge Size Tons
7-9	14:55:48.65	44°03'.32	74°02'..92	1788	4.5
7-11	14:55:42.29	.36	.86	1788	2.75
7-12	14:38:00.89	.38	.84	1823	1.23
7-13	15:15:47.96	.32	.84	1823	0.98
7-17	14:45:54.63	.35	.91	1753	1.25
7-18	14:50:43.17	.34	03'.00	1718	2.0
7-20	15:10:25.89	.33	02'.89	1788	1.0
7-23	15:05:03.57	.40	.80	1822	3.6
7-24	15:12:15.32	.40	.75	1857	1.2
7-31	14:42:38.24	.32	.91	1780	0.9
	15:00:24.29	.31	.89	1822	2.4
8-2	14:38:37.31	.33	.99	1716	1.2
8-3	15:05:09.99	.39	.75	1857	0.75
8-14	15:04:45.47	.35	.86	1788	4.4
	15:15:07.80	.37	.92	1788	0.75
	15:51:26.32	.37	.72		9.2
8-23	15:07:06.03	.37	.79	1822	2.8
8-27	15:15:19.10	.34	.92	1748	0.75
	15:34:51.43			1748	1.4
8-29	15:23:28.82	.34	.81	1818	1.9
8-31	14:49:38.21	.33	03'.01	1716	2.5

, Topographic Corrections: P_n=-.11 sec
S_n=-.18 sec

TABLE II-C

List of Shots

Bethlehem Quarry Co.
Milroy, Pennsylvania

Date	Time EST	Latitude	Longitude	Elevation Feet	Charge Size Tons
8-16151	14:47:25.00	40°42'.85N	77°33'.26 W	760	42.7
10-3-51	16:18:44.70				43.3
11-19-51	16:03:26.26				25.3
8-21-52	14:01:08.90				22.0
8-21-52	14:49:55.46				32.0
4-20-53	16:01:09.62				46.1

Topographic Correction P_n -.02 Sec.

S_n -.03 Sec.

TABLE III-A

Tahawus-west Profile

Station Name	Distance Km	P_1	Residuals Linear Velocity Gradient To-Tc	P_n	S_1	Residual Linear Velocity Gradient To-Tc	S_n
Santanoni	4.29	0.73	+0.05				
Moose Pond	11.58	1.87	+ .03				
	11.40	1.90	+ .09				
	11.72	1.89	+ .03				
Duck Lake	32.96	5.21	- .02				
Legion Camp	41.12	6.53	+ .01		11.9	+0.2	
	41.32	6.53	- .02		11.9	+0.2	
Lake Marion	54.37	8.70	+ .09		15.8	+0.4	
	23.48	3.83	+ .11				
Star Lake	81.67	12.91±0.27 14.1	+ .01				
Pitcairn	95.70	15.12±0.15	+ .03		27.8-1.4 +0	+0.8	
Antwerp	125.60	19.68 ±0.24	- .05		35.0	-0.3	40.4
Theresa	141.87	22.08	- .15		40.1	+0.3	47.6
Fisherman's Landing	159.63	24.85	- .08		44.4	-0.3	
Gananoque	171.86	26.88	+ .11		48.2	+0.1	50.3
Odessa	220.47			33.75*			60.4
Roslin	265.26	40.5		38.8±0.3*			70.3

* Topographic correctinn applied

TABLE III-B

Travel-Time-Distance Data
Tahawus-south Profile

Station Name, N. Y.	Distance Km	P_1	P_n	S_1	Residuals Linear Velocity Gradient To-Tc	S_n
Tahawus Club	11.05	1.69		3.2	+0.1	
Aiden Lair	18.00	2.68		4.6	-0.4	
Minerva	27.63	4.41		7.7	0.	
Sodom	45.53	7.21		12.6	-0.1	
Thurman	62.39	9.80	14.5	17.3	-0.1	
Roundtop	71.80	10.97	15.9	20.3	+0.9	
Stony Creek	77.20	11.93				
Hadley Hill	78.88	12.37 13.4	17.1	22.2	+0.3	
Fox Hill	95.92	15.12		26.5	-0.2	
Barkersville	106.49 106.47	16.66 16.71	20.8	29.6 29.3	0 -0.3	
Galway	114.49	18.03	20.6	31.2	-0.6	
Rynex Corners	134.99	21.43	24.3	37.6	+0.1	
Diamond Rock	145.18 145.23	23.26 23.01		41.1 40.8	+0.8 +0.5	
Altamont	153.26 153.37	24.33 24.33		42.7 42.2	+0.2 -0.4	
Averill Park	163.13	26.08	27.3	44.9	-0.3	
Westerlo	169.66	26.83		46.8	-0.2	
Malden Bridge	181.39	28.63	29.5	50.3	0	52.3
W. Copake	218.27		34.04			59.8
Fishkill	281.43		42.25			76.7

TABLE III-C

Travel-Time-Distance Data
Milroy Profile

Station Name	Distance Km	P_1	P_n	S_1	Residuals Linear Velocity Gradient To-Tc	S_n
Middle Creek, Pa.	25.23	4.35				
Freeburg, Pa.	52.52	8.62		16.0	+0.9	
Gear Gap, Pa.	93.99	14.99 16.0 15.5		27.3	+0.3	
Oneida, Pa.	122.20	20.43	22.4	35.2	+0.1	
Hudsondale, Pa.	147.92	24.26	25.3	42.6	+0.2	44.9
Aquashicola, Pa.	166.31	27.47	27.7	47.5	-0.1	49.0
Kellersville, Pa.	192.27	31.5	30.77	54.5	-0.4	54.0
Millbrook, N. J.	210.73		33.00±.21	60.31	+0.3	58.47
Long Valley, N. J.	234.49		36.05±.23	66.8	-0.2	
Tranquility, N. J.	235.56		36.19 36.22	66.5	-0.4	63.7
Boonton, N. J.	265.39	43.6	39.95	74.5	-0.6	69.6
Palisades, N. Y.	309.09		45.2	86.7	-0.2	79.2
			45.2	87.3	+0.4	79.1
		51.4	45.0	87.1	+0.1	79.3
		51.6	44.9			78.6
			45.0			80.3
		51.2				

TABLE IV

Summary of Travel Time Equations and Crustal Thickness Calculations
Δ in km, T in seconds, [ ] indicates velocity assumed on basis of other measurements

Profile	Homogeneous Crust P_1	Homogeneous Crust S_1	Poisson's Ratio	Crust with Velocity Gradient P_1	Crust with Velocity Gradient S_1
Tahawus - west	$T=0.12\pm0.02 + \frac{\Delta}{6.43\pm0.01}$ $T=\frac{\Delta}{6.39}$ *	$T=0.64\pm0.24 + \frac{\Delta}{3.62\pm0.03}$	0.266 ± 0.005	$T=0.1587\Delta - 10.2\times10^{-8}\Delta^3$ $V_o=6.30$ km/sec $g=248.0\times10^{-4}$ km/sec/km	$T=0.2830\Delta - 10.6\times10^{-8}\Delta^3$ $V_o=3.53$ km/sec $g=106.1\times10^{-4}$ km/sec/km
Tahawus - south	$T=0.12\pm0.04 + \frac{\Delta}{6.28\pm0.02}$ $T=\frac{\Delta}{6.31}$ *	$T\pm0.12 + \frac{\Delta}{3.60\pm0.01}$	0.255 ± 0.004		$T=0.2784\Delta - 3.97\times10^{-8}\Delta^3$ $V_o=3.59$ km/sec $g=66.5\times10^{-4}$ km/sec/km
Milroy	$T=0.18\pm0.13 + \frac{\Delta}{6.01\pm0.03}$ $T=\frac{\Delta}{6.04}$ *	$T=1.46\pm0.16 + \frac{\Delta}{3.61\pm0.01}$	0.218 ± 0.007		$T=0.2884\Delta - 7.65\times10^{-8}\Delta^3$ $V_o=3.47$ km/sec $g=87.5\times10^{-4}$ km/sec/km

* forced through origin

TABLE IV (Cont'd)

Profile	Mantle Velocity Pn	Mantle Velocity Sn	Poisson's Ratio	Crustal Thickness P_1, Pn	Crustal Thickness S_1, Sn**
Tahawus-west	$T=6.8+\frac{\Delta}{[8.2]}$	$T=13.55\pm0.19+\frac{\Delta}{4.68\pm0.02}$		$[H_p=34.8$ km$]$	$H_{1s}=2.2\pm0.9$ km ^{o} $H_{2s}=35.9\pm2.7$ km $H_s=38.1\pm3.6$ km
Tahawus-south	$T=7.10\pm0.21+\frac{\Delta}{8.07\pm0.10}$	$T=13.3+\frac{\Delta}{[4.7]}$		$H_p=36.0\pm2.0$ km	$[H_s=37.2$ km$]$
Milroy	$T=7.45\pm0.14+\frac{\Delta}{8.21\pm0.02}$	$T=13.34+\frac{\Delta}{4.69\pm0.03}$	0.258±0.006	$H_{1p}=1.4\pm1.0$ km^{oo} $H_{2p}=31.3\pm2.2$ km $H_p=32.7\pm3.3$ km	$H_{1s}=5.1\pm0.7$ km^{o} $H_{2s}=31.3\pm3.6$ km $H_s=36.3\pm4.3$ km

** $H_s=H_{1s}+H_{2s}$

o $V_{1s}=3.2$ km/sec, assumed

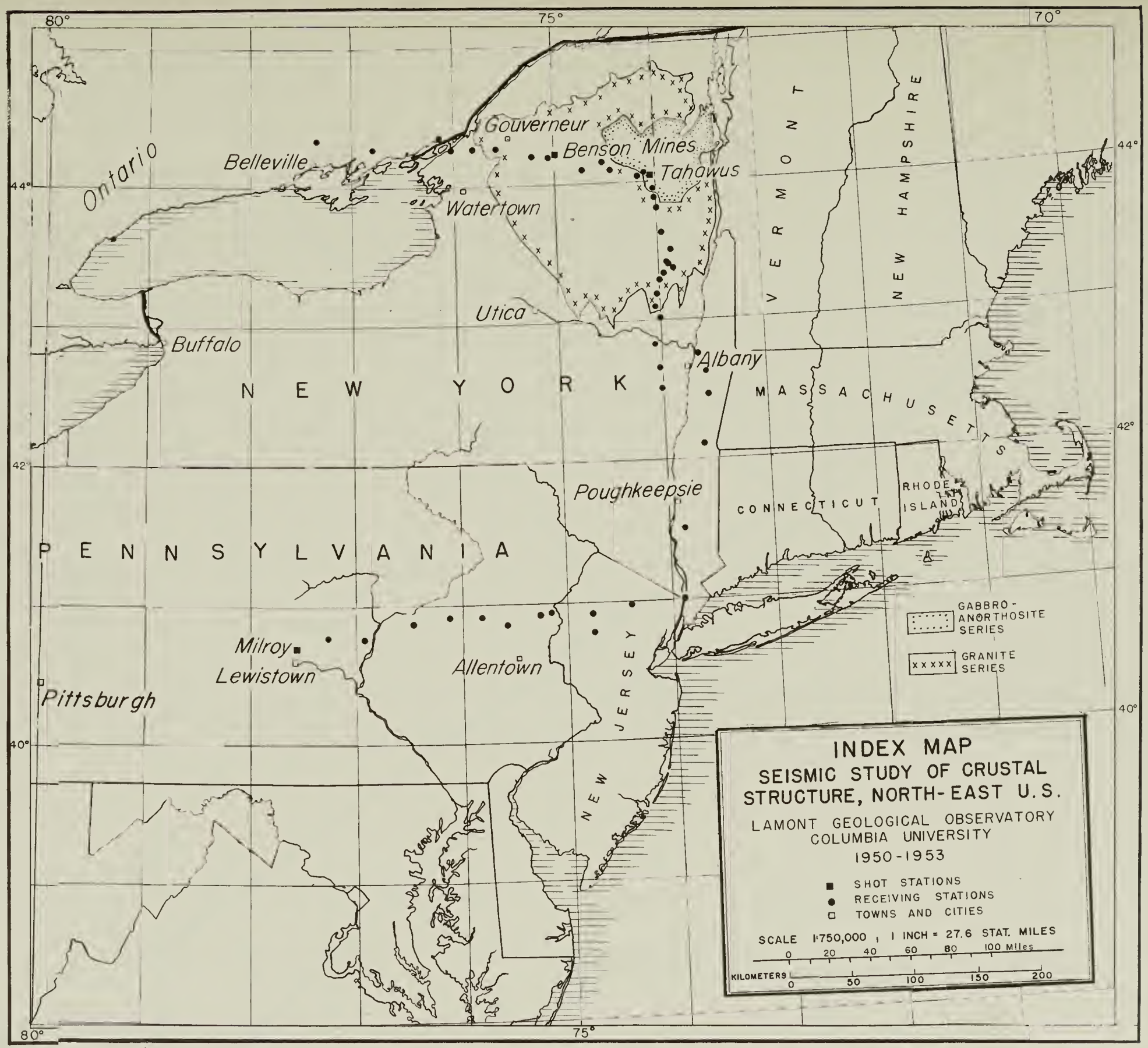
oo $V_{1p}=5.6$ km/sec, assumed

TABLE V

Compressional Wave Velocity in Anorthosite

Tahawus, N. Y.

Date	Sound Path Shot to	Distance X_i in feet	Arrival Time T_i	Velocity ft/sec
Aug. 27, 1951	geophone	633	16:15:19.097	
	Station 1b	4969	16:15:19.240	21,390
	Station 1c	1511	16:15:19.072	
	Station 1d	1517	16:15:19.085	
Aug. 27, 1951	Station 1b	5030	16:34:51.604	
	Station 1c	1929	16:34:51.465	22,140
	Station 1d	1122	16:34:51.427	
Aug. 29, 1951	Station 1b	5360	16:23:28.987	
	Station 1c	1693	16:23:28.819	21,700
	Station 1d	1669	16:23:28.816	
			Mean	21,750 ft/sec
				6.63±.09 km/sec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70°
44°
42°
40°
Ontario
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Gouverneur
Benson Mines
Tahawus
Watertown
Utica
Buffalo
Albany
VERMONT
NEW HAMPSHIRE
NEW YORK
MASSACHUSETTS
Poughkeepsie
CONNECTICUT
RHODE ISLAND
PENNSYLVANIA
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1950-1953
SHOT STATIONS
RECEIVING STATIONS
TOWNS AND CITIES
SCALE 1:750,000 , 1 INCH = 27.6 STAT. MILES
0 20 40 60 80 100 Miles
KILOMETERS 0 50 100 150 200

Figure 1.

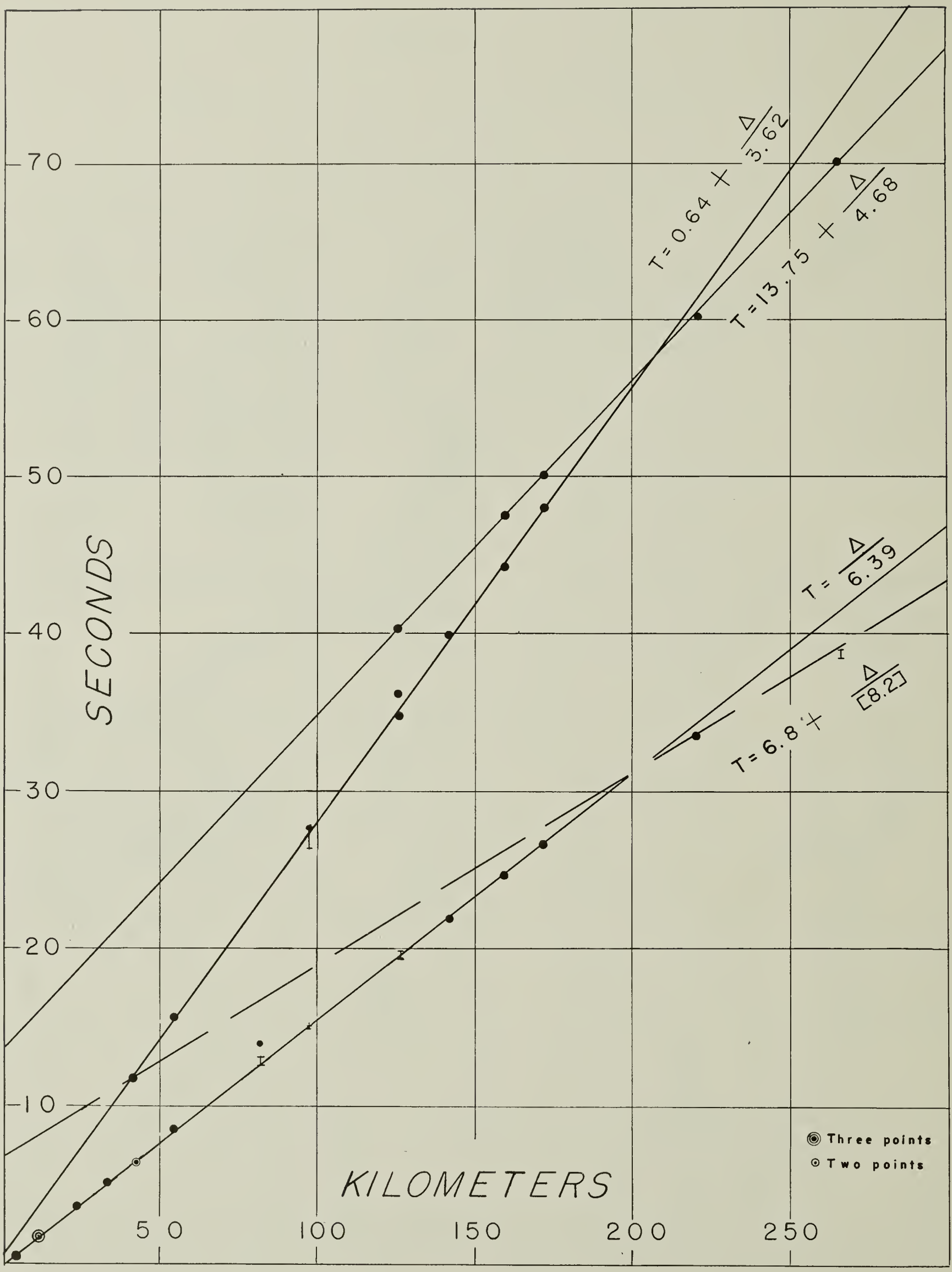

Figure 2. Travel Time-Distance Curve, Tahawus-west Profile

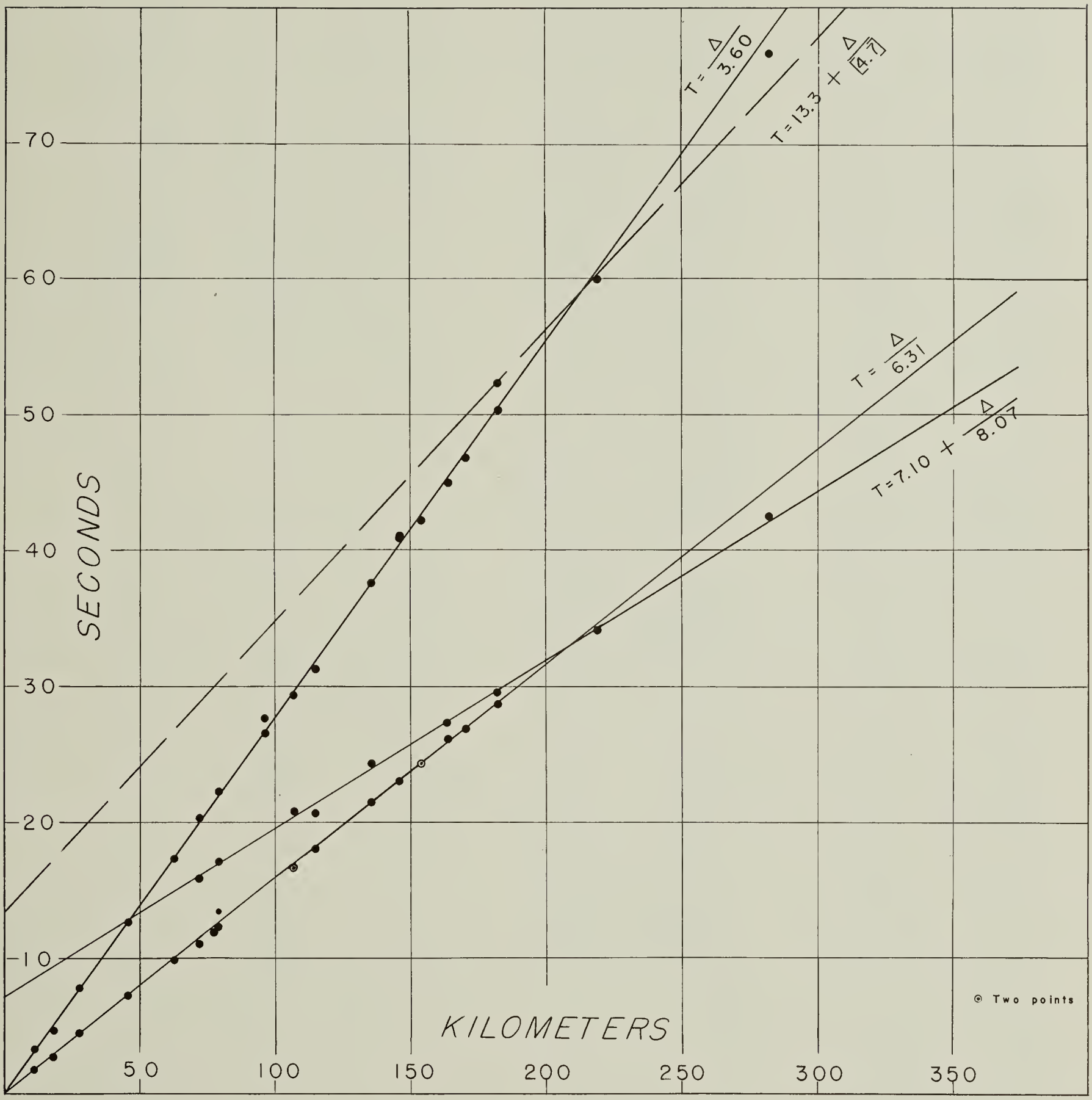

Figure 3. Travel Time-Distance Curve, Tahawus-south Profile

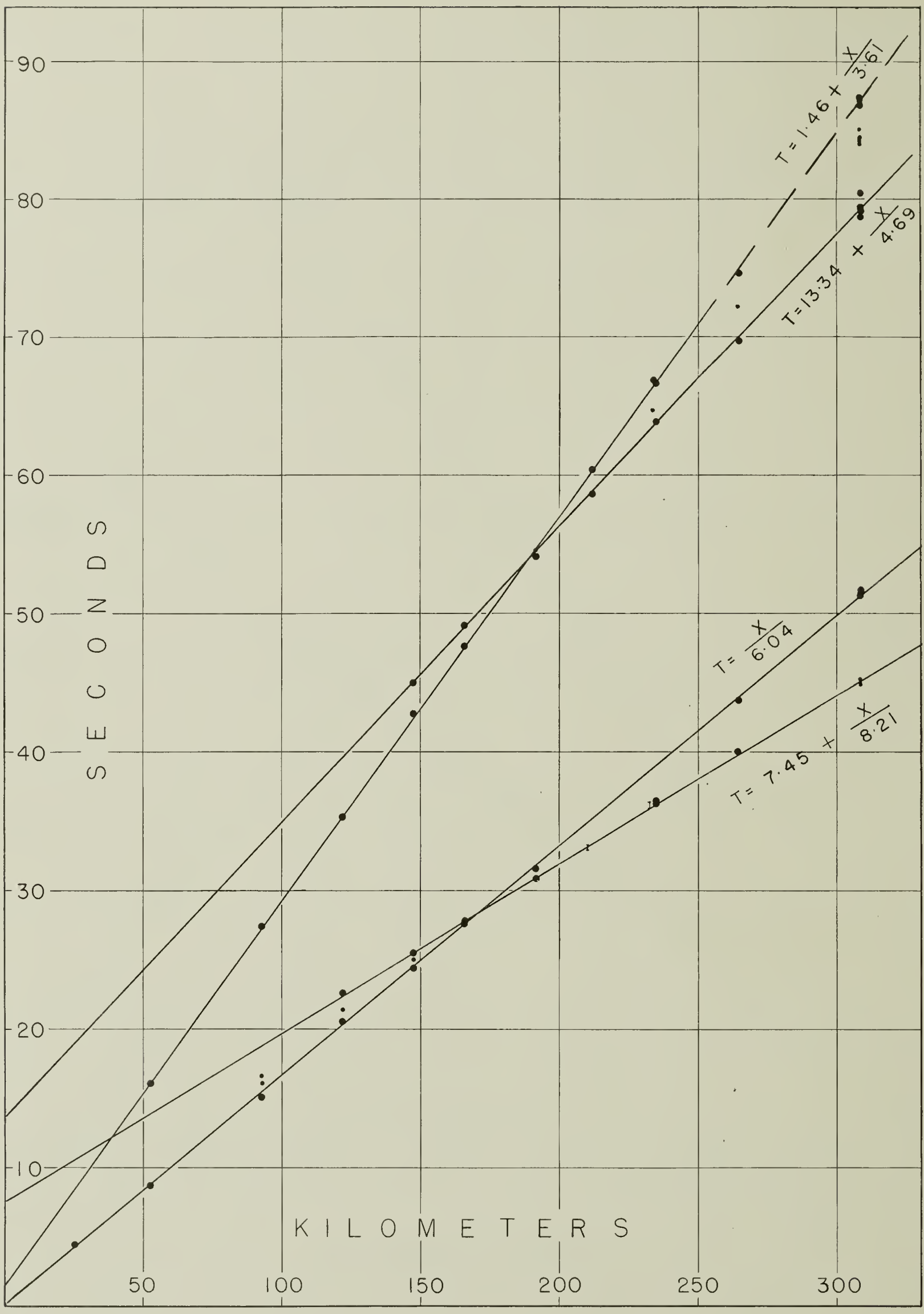

Figure 4. Travel Time-Distance Curve, Milroy Profile

Figure 5. Seismograms

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